Power MOSFET Thermal Design and Attachment of a Thermal Fin

Description

This document explains of power MOSFETs' thermal design and attachment of a thermal fin.

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1. Thermal Design and Attachment of a Thermal Fin

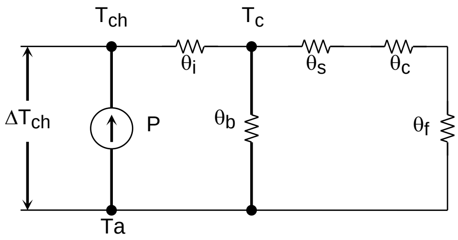
1.1. Maximum Allowable Power Dissipation and Radiation Equivalent Circuit

At thermal equilibrium, the maximum power dissipation P_D(max) of a power MOSFET can be expressed as follows in terms of the ambient temperature, T_a, the power MOSFET's maximum channel temperature T_{ch}(max) and the channel-to-ambient thermal resistance $R_{th(ch-a)}$ as determined by heat dissipation conditions discussed in this section.

$$P_D\,(\max)(T_a) = \frac{T_{ch}(max) - T_a}{R_{th(ch-a)}} \qquad \ldots(1)$$

Heat flow can be modeled by analogy to an electrical circuit. Using this model, the heat flow from the channel of a MOSFET to the ambient air is derived from thermal resistances and thermal capacitances.

Figure 1.1 shows a radiation equivalent circuit in the thermal steady state.



θ_i: Internal thermal resistance (channel-to-package)
θ_b: External thermal resistance (package-to-ambient air)
θ_s: Thermal resistance of an insulation shield
θ_c: Contact thermal resistance (at the interface with a thermal fin)
θ_f: Heat sink's thermal resistance

Figure 1.1 Radiation Equivalent Circuit

From the equivalent circuit of Figure 1.1, the channel-to-ambient thermal resistance $R_{th(ch-a)}$ can be calculated as follows:

$$R_{th(ch-a)} = \theta_i + \frac{\theta_b(\theta_s + \theta_c + \theta_f)}{\theta_b + \theta_s + \theta_c + \theta_f} \qquad \ldots(2)$$

Since no heat sink is generally used for power MOSFETs in a thermally conductive package Rth(ch-a) can be calculated as follows:

$$R_{th(ch-a)} = \theta_i + \theta_b \qquad \ldots(3)$$

The catalog of power MOSFETs in thermally conductive packages shows their maximum allowable power dissipation at an ambient temperature T_a of 25°C. When this power dissipation value is not specified, the P_D(max) value can be expressed in terms of $R_{th(ch-a)}$ and T_{ch}(max):

$$P_D\,(\max)(T_a = 25°\mathrm{C}) = \frac{T_{ch}(max) - 25}{R_{th(ch-a)}}$$

The case-to-ambient thermal resistance θ_b varies with the material and shape of the case. Generally, θ_b is significantly larger than θ_i, θ_c, θ_s and θ_f. Therefore, in practice, Equation (2) can be simplified as follows for packages to which a heat sink is attached:

$$R_{th(ch-a)} = \theta_i + \theta_s + \theta_c + \theta_f \qquad \ldots(4)$$

In dealing with direct current dissipation, it is possible to realize a radiation design satisfying the maximum given by Equation (4). When power MOSFETs are used in a pulse circuit, great care is required to ensure that the peak value of T_{ch} does not exceed $T_{ch}(max)$.

1.2. Pulse Response of Channel Temperature

Generally, the thermal impedance of a power MOSFET is modeled as a distributed constant circuit as shown in Figure 1.2.

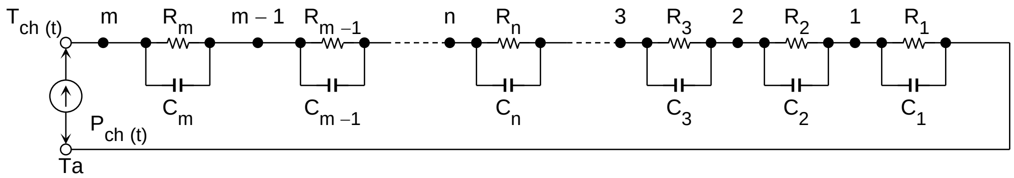


Figure 1.2 Thermal Impedance of a Power MOSFET

When a power loss $P_{ch}(t)$ shown in Figure 1.3 is applied to the circuit in Figure 1.2, the change in temperature $T_{ch}(t)$ that appears at the m-th parallel RC circuit under stable thermal conditions can be calculated as follows:

1. In the region where $P_{ch}(t) = P_0$,

$$T_{ch}(t) = \sum_{n=1}^{m} (P_0 R_n - T_n(min)) \left\{1 - \exp\left(-\frac{t}{C_n R_n}\right)\right\} + T_n\,(min) \quad \text{... (5)}$$

2. In the region where $P_{ch}(t) = 0$

$$T_{ch}(t) = \sum_{n=1}^{m} T_n(max) \cdot \exp\left(-\frac{t}{C_n R_n}\right) \quad \text{...(6)}$$

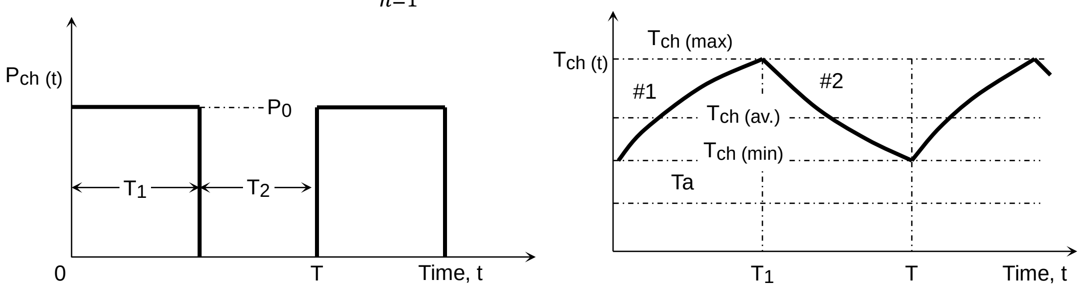


Figure 1.3 Change in Temperature Caused by Applying Pulse

For typical power MOSFETs, the actual value of $T_{ch}(t)$ can be approximated by substituting n=4. But if the C and R values are indefinite, it is difficult to calculate T_{ch}. Therefore, T_{chpeak} is generally estimated using transient thermal resistance as follows.

Figure 1.4 shows an example of typical transient thermal resistance characteristics. Suppose that a single rectangular pulse (with a pulse width of T_1 and a peak power loss of P_0) is applied. From the figure, we read the transient thermal resistance at a pulse width of T_1, $r_{th}(T_1)$, and then use Equation (7) to calculate T_{chpeak}.

$$T_{chpeak} = r_{th}(T_1) \cdot P_0 + T_a \qquad (7)$$

When a repetitive pulse train with a cyclic period of T is applied as shown in Figure 1.3, T_{chpeak} in a thermally stable state is calculated as follows:

$$T_{chpeak} = P_0\left[\frac{T_1}{T}R_{th(ch-a)} + \left(1-\frac{T_1}{T}\right)\cdot r_{th}(T+T_1) - r_{th}(T) + r_{th}(T_1)\right] + T_a \quad \dots(8)$$

Great care should be exercised in the thermal design for a pulse circuit to ensure that T_{chpeak} does not exceed T_{ch}(max) of a power MOSFET.

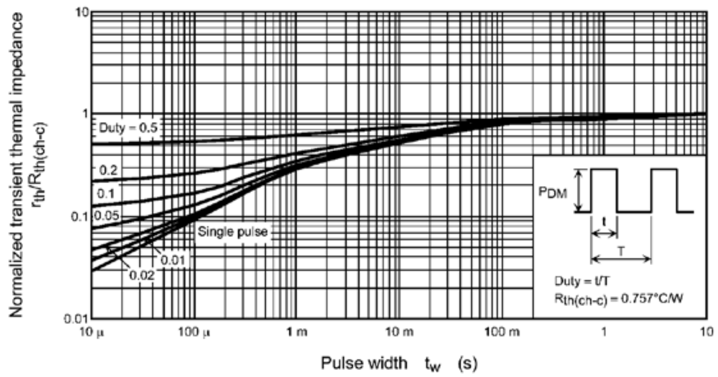


Figure 1.4. Transient Thermal Resistance Curves

In practice, P_{ch} (t) may not be a rectangular wave for applications of power MOSFETs.
In such cases, approximate the power loss waveform as a rectangular wave as shown in Figure 1.5 and use Equation (8) to estimate T_{chpeak}.

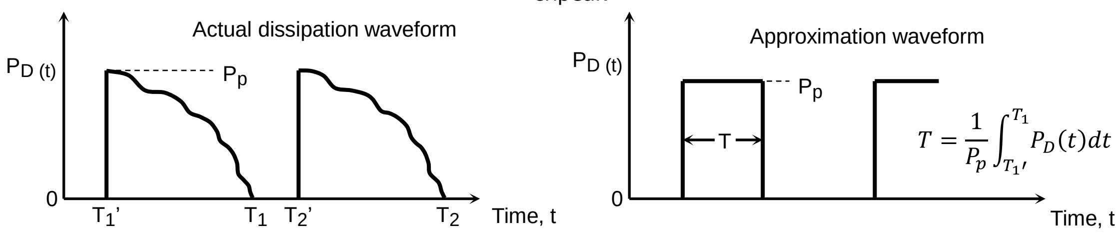


Figure 1.5 Approximation of a Power Loss Waveform

In order to accurately convert a power loss wave into a square wave, it is necessary to perform integration. However, if the power loss waveform is nearly a sine-wave or triangular-wave P_{ch}(t) can be estimated as shown below.

In (a) and (b), a peak value of $0.7P_D$ and a pulse width of either 0.91t or 0.71t are assumed (to obtain a square pulse with the same area).

In (c) and (d), the peak value is the same before and after conversion, the pulse width is approximated as 0.63t or t/2 (to obtain a square pulse with the same area).

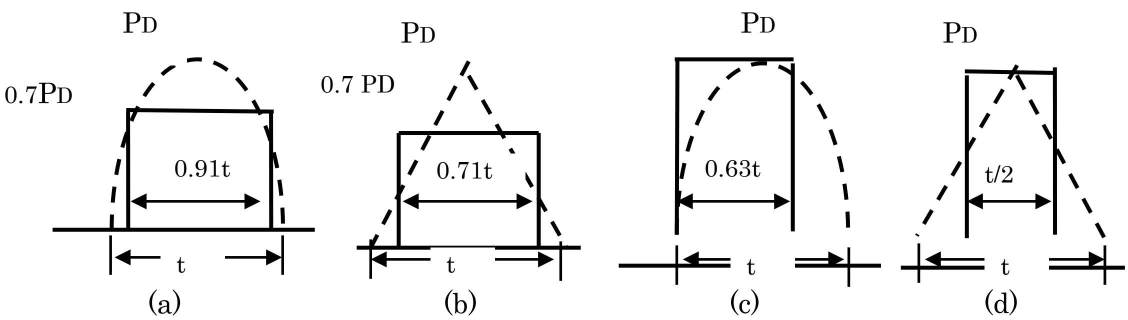
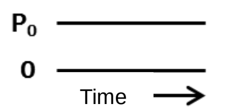
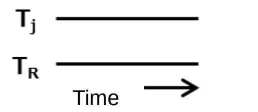
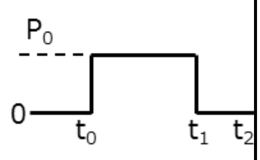
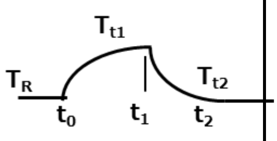
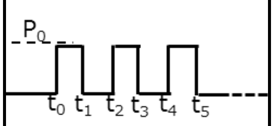
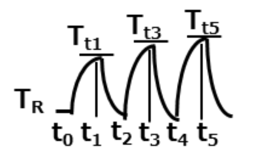
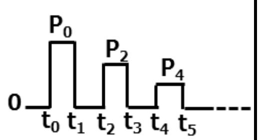
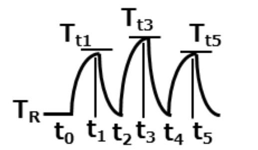
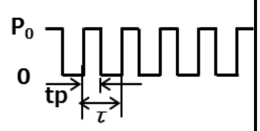
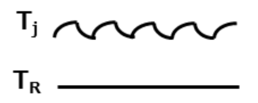
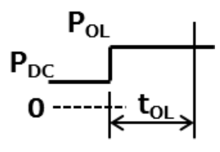
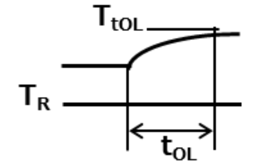
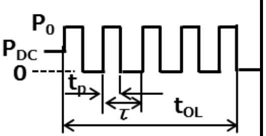
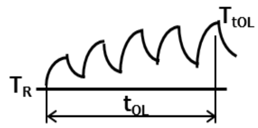


Figure 1.6 Waveform Approximation

Table 1.1 Basic Equations for Calculating Load Current

Power Applying Pattern	Junction Power Loss Waveform	Junction Temperature Rise (T_R: Reference temperature)	Junction Temperature and Power Loss R_{th} = Steady-state Thermal Resistance $r_{th}(t_1)$ = Transient Thermal Impedance at Time t_1 $r_{th}(t_2-t_1)$ = Transient Thermal Impedance at Time (t_2-t_1)
(a) Continuous load			$T_j - T_R = P_0 R_{th}$ $P_0 = (T_j - T_R) / R_{th}$
(b) Single-shot pulse			$T_{t1} - T_R = P_0 r_{th}(t_1)$ $T_{t2} - T_R = P_0[r_{th}(t_2) - r_{th}(t_2 - t_1)]$ $P_0 = (T_{t1} - T_R) / r_{th}(t_1)$
(c) Short pulse train with an equal amplitude			$T_{t1} - T_R = P_0 r_{th}(t_1)$ $T_{t3} - T_R = P_0[r_{th}(t_3) - r_{th}(t_3 - t_1) + r_{th}(t_3 - t_2)]$ $T_{t5} - T_R = P_0[r_{th}(t_5) - r_{th}(t_5 - t_1) + r_{th}(t_5 - t_2) - r_{th}(t_5 - t_3)$ $+ r_{th}(t_5 - t_4)]$
(d) Pulse train with an unequal amplitude			$T_{t1} - T_R = P_0 r_{th}(t_1)$ $T_{t3} - T_R = P_0 r_{th}(t_3) - P_0 r_{th}(t_3 - t_1) + P_2 r_{th}(t_3 - t_2)]$ $T_{t5} - T_R = P_0 r_{th}(t_5) - P_0 r_{th}(t_5 - t_1) + P_2 r_{th}(t_5 - t_2)$ $- P_2 r_{th}(t_5 - t_3) + P_4 r_{th}(t_5 - t_4)]$
(e) Long pulse train with an equal amplitude (approximate solution)			$T_j - T_R = P_0[(t_p R_{th}/\tau) + (1 - t_p/\tau) r_{th}(\tau + t_p) - r_{th}(\tau) + r_{th}(t_p)]$ $P_0 = (T_j - T_R)/[(t_p R_{th}/\tau) + (1 - t_p/\tau) r_{th}(\tau + t_p) - r_{th}(\tau) + r_{th}(t_p)]$
(f) Overload with continuous load (Non-pulsed)			$T_{tOL} - T_R = P_{DC} R_{th} + (P_{OL} - P_{DC}) r_{th}(t_{OL})$ $P_{OL} = [(T_{tOL} - T_R - P_{DC} R_{th}) / r_{th}(t_{OL})] + P_{DC}$
(g) Overload with continuous load (Pulsed) (Approximate solution)	 $P_0 t_p / \tau > P_{DC}$		$T_{OL} - T_R = P_{DC} R_{th} + P_0[(t_p/\tau - P_{DC}/P_0) r_{th}(t_{OL})$ $+ (1 - t_p/\tau) r_{th}(\tau + t_p) - r_{th}(\tau) + r_{th}(t_p)]$ $P_0 = [T_{tOL} - T_R - P_{DC}\{R_{th} - r_{th}(t_{OL})\}] /$ $[(t_p/\tau) r_{th}(t_{OL}) + (1 - t_p/\tau) r_{th}(\tau + t_p) - r_{th}(\tau) + r_{th}(t_p)]$

Calculation Example:

The data necessary for calculation are the waveforms of drain-source voltage and the drain current, the ambient temperature, the thermal resistance data for the heat sink, and the operating conditions. Channel temperature can be estimated with Equation (8) using these data.

If the result is less than the rated maximum channel temperature T_{ch}(max), you can determine that the device can be used.

Here is an example of calculation based on a typical waveform under continuous operation for switching power supplies.

Typical waveform: Device without a heat sink

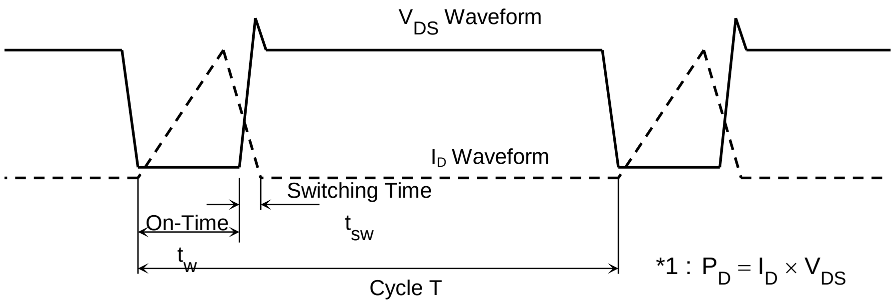


Figure 1.7 Typical Waveform

First, approximate the power loss[*1] from the above waveform as a square wave and then use Equation (8) to calculate the channel temperature. Figure 1.8 shows the waveform for power loss and the square waveform approximated from it.

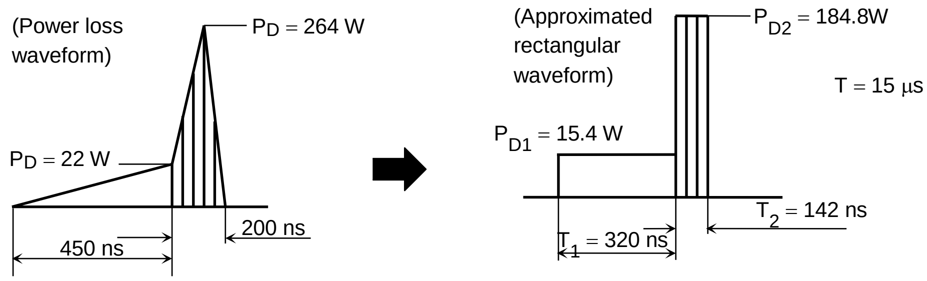


Figure 1.8 Approximated Rectangular Waveform

If a regularly repetitive rectangular waveform as shown in Figure 1.3 is applied to a device, Equation (8) can be used to calculate the peak of the channel temperature increase. If multiple rectangular waveforms mentioned above are periodically applied, it is necessary to create a separate model and apply the equation to that model.

Create a model by combining an average power loss with two or so cycles in which the power loss exceeds the average. For the above rectangular waveform, use the following type of approximate model shown in Figure 1.9 for calculation.

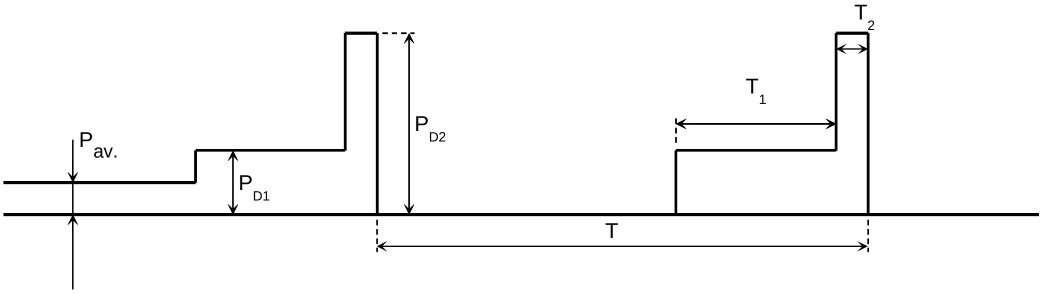


Figure 1.9 Power Loss Model

$$P_{av.} = \frac{1}{T}\int_0^T (P_{D1} + P_{D2})dt = \frac{1}{T}(T_1 P_{D1} + T_2 P_{D2})$$

Calculate as given below; the average power loss is applied for an infinite period $P_{av.}$ (#1) and the repetitive waveform is applied for two cycles thereafter.

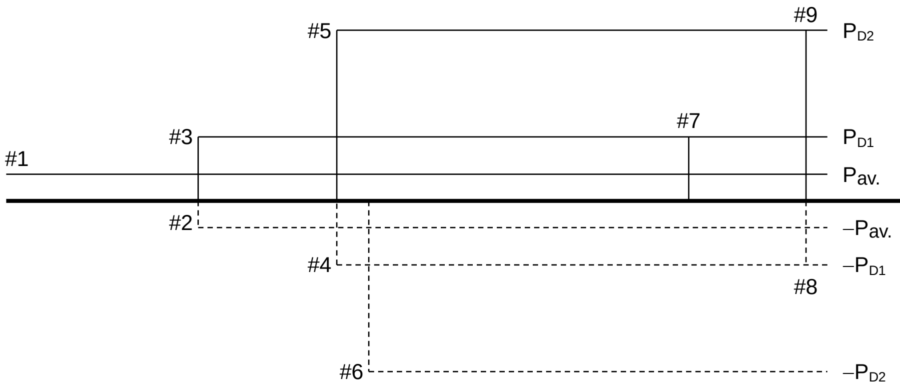


Figure 1.10 Relationship of Stacked Waveforms and Time

$$\Delta T_{ch(peak)} = \underbrace{P_{av.} \times R_{th(ch-a)}}_{\#1} \underbrace{- P_{av} \times r_{th}(T + T_1 + T_2)}_{\#2} \underbrace{+ P_{D1} \times r_{th}(T + T_1 + T_2)}_{\#3}$$

$$\underbrace{-P_{D1} \times r_{th}(T + T_2)}_{\#4} \underbrace{+ P_{D2} \times r_{th}(T + T_2)}_{\#5} \underbrace{- P_{D2} \times r_{th}(T)}_{\#6} \underbrace{+ P_{D1} \times r_{th}(T_1 + T_2)}_{\#7}$$

$$\underbrace{-P_{D1} \times r_{th}(T_2)}_{\#8} \underbrace{+ P_{D2} \times r_{th}(T_2)}_{\#9} \quad \dots(9)$$

To calculate channel temperature, the $R_{th(ch\text{-}a)}$ and $r_{th}(t)$ values are necessary as shown in Equation (9).

$r_{th}(t)$: Obtain from the transient thermal resistance curves provided in individual technical datasheets.

If the pulse width is shorter than the range shown in the datasheet, calculate as follows:

$$r_{th}(t) = r_{th}(T) \times \sqrt{\frac{t}{T}}$$

T: Shortest period of time shown in the transient thermal resistance curve

$r_{th}(T)$: transient thermal resistance at time T

The thermal resistance values shown in the equivalent thermal circuit of Figure 1.1 can be explained as follows:

(1) Channel-to-case thermal resistance (internal thermal resistance): θ_i

The internal thermal resistance θ_i from the channel of a power MOSFET to the case depends on the structure and materials of the MOSFET, board assembly, case materials and other factors. Each power MOSFET has its own thermal resistance characteristics.

To measure internal thermal resistance, the case of the power MOSFET must be cooled to maintain a constant temperature.

When the case temperature T_c is held at 25°C, the maximum allowable power dissipation, P_D(max), of a power MOSFET can be calculated using Equation (10).

$$P_D(max) = \frac{T_{ch}(max) - T_c}{\theta_i} = \frac{T_{ch}(max) - 25}{\theta_i} \quad \ldots(10)$$

In catalogs for power MOSFET, the maximum allowable drain dissipation is specified at a temperature of 25°C with specific condition in datasheets.

Note: The symbol $R_{th(ch-c)}$ may be used to represent channel-to-case thermal resistance.

(2) Contact thermal resistance: θ_c

Contact thermal resistance θ_c varies according to the condition of the contact surface between the case of the power MOSFET and the heat sink. This condition is greatly affected by factors such as the coarseness and the fastening method. For example, the influence of factors such as coarseness and unevenness can be reduced by the application of silicone grease. However, power MOSFETs (such as surface-mounted devices) are not designed to be attached directly to heat sinks, and contact thermal resistance can be considerably large in case of poor attachment to the heat sink.

(3) Insulation plate’s thermal resistance: θ_S

If it is necessary to provide electrical insulation between a power MOSFET and a heat sink, an insulation plate must be inserted between them.

The thermal resistance of this insulation plate θ_S varies with the materials, thickness and area of the plate. Sometimes the thermal resistance value of the insulation plate can be significant, so it must not be ignored.

(4) Heat sink thermal resistance: θ_f

The thermal resistance of a heat sink can be considered as the distributed thermal resistance of the heat path from the surface of a heat sink to ambient air. The thermal resistance of a heat sink is decided by its material, shape, condition of ambient, and the effective area of the heat sink.

Figure 1.11 shows an example of thermal resistance data measured for a power MOSFET standing vertically at the center of the heat sink.

In recent years, various thermal heat sinks have been available from many vendors. These data are useful when using a heat sink.

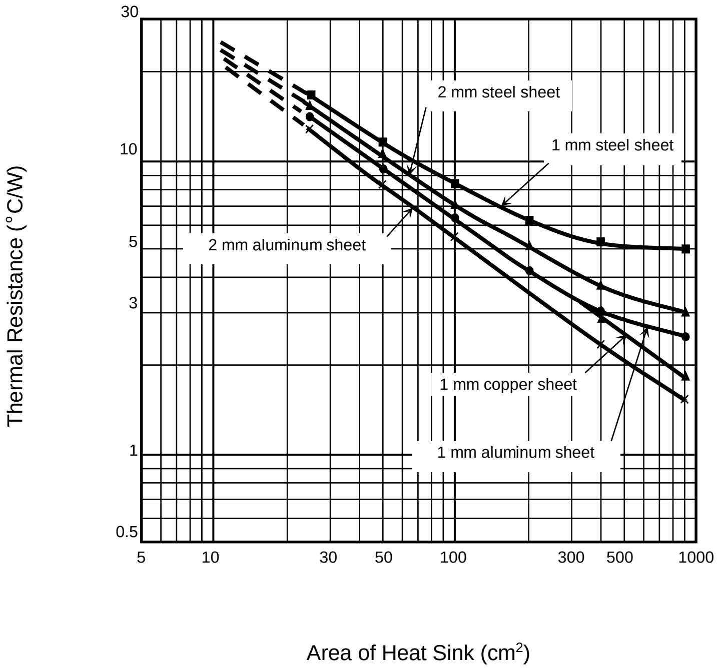


Figure 1.11 Area of Heat Sink and Thermal Resistance θ_f

1.3. Attaching to the Heat Sink

It is recommended to attach the heat sink in accordance with the following points. For example, if the heat sink has burrs or hollows, if its attachment profile is the wrong size, or the tightening torque of the MOSFET is not adequate, the MOSFET can be warped, causing the destruction of a pallet or resin, or the degradation of adhesion between the resin and the frame.

(1) Flatness of heat sink

The surface on which a device is to be attached must be sufficiently smooth. If it is warped or substantially uneven or if any foreign matter, such as pressing burrs or cutting chips, are present, the device could be destroyed in the worst case. To prevent this problem, the flatness of the surface where the device is attached should be 50 µm or less.

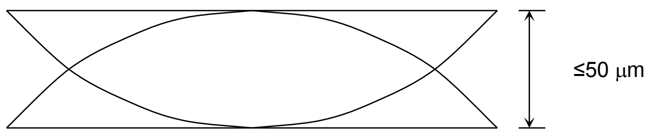


Figure 1.12 Warp of Heat Sink

(2) Mounting hole

Intrusion around the mounting holes resulting from machining should be 50 µm or less in size, and the mounting holes should not be unnecessarily large. If such conditions are unavoidable, be sure to insert a square washer.

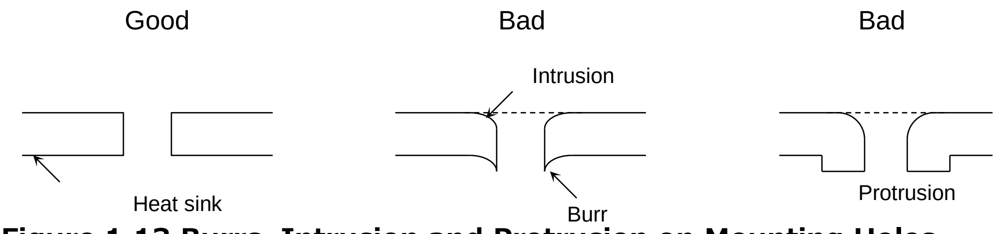


Figure 1.13 Burrs, Intrusion and Protrusion on Mounting Holes

(3) Screws

Screws used to attach MOSFETs to a heat sink are generally classified as machine screws and tapping screws. When tapping screws are used, care should be exercised to ensure that the tightening torque will not exceed the maximum allowable limit. Do not use special screws such as flat-head and round-head screws because they apply excessive stress on the device.

(4) Insulation spacers

Use insulation spacers with sufficient mechanical strength.

(5) Insulation washers

Use insulation washers suitable for the device.

(6) Grease

Use grease that is not prone to base oil separation so that the device is not adversely affected internally.

(7) Tightening torques

The tightening torques should be less than the values shown in Table 1.2 so as not to cause stress on the device and to achieve the desired thermal resistance.

Table 1.2 Maximum Torques by Packages

Package **Name**	**Screw Tightening Torque (max)(in N·m)**
TO-220	0.6
TO-220SIS	0.6
TO-3P(N)	0.8
TO-247	0.8
TO-3P(L)	0.8

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